Effects of ring shadowing on the detection of electrostatic discharges at Saturn

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[1]   A long-standing discrepancy exists in determinations from observations and modeling of the diurnal variation of the peak electron density of Saturn's ionosphere. Using a new Saturn-Thermosphere-Ionosphere-Model (STIM), we examine the suggestion by Burns et al. (1983) that Saturn's rings shadow its ionosphere causing radio penetration "holes", thereby allowing lightning-induced radio signals (Saturn electrostatic discharges, SEDs) to escape. This lessens the need to invoke globally enhanced loss processes to account for Voyager era observations of nighttime peak density (N_{max}) as low as 10^3 e/cm^3 from the SEDs. We find radio frequency "windows" produced by ring shadowing that were narrow and confined to low latitudes during the Voyager era, but are now broadly distributed over northern mid-latitudes during the Cassini era. If lightning sources occur only at near-equatorial latitudes, then the far less frequent detection of SEDs by Cassini early in its mission would be consistent with the current ionospheric morphology.   **Citation:** Mendillo, M., L. Moore, J. Clarke, I. Mueller-Wodarg, W. S. Kurth, and M. L. Kaiser (2005), Effects of ring shadowing on the detection of electrostatic discharges at Saturn, *Geophys. Res. Lett.*, *32*, L05107, doi:10.1029/2004GL021934.

1. Introduction

[2]   Planets emit radio waves into space by a variety of natural means. There is a rich literature describing the radio emissions arising from the energetic charged particles that cause the aurora along high latitude magnetic field lines on Earth, Jupiter and Saturn (called Auroral Kilometric Radiation (AKR) at Earth, broadband kilometric, hectometric, and decametric radiation at Jupiter, and SKR at Saturn). Lightning discharges deep in a planet's atmosphere also generate radio waves that can escape into space, with cases found at Earth, Saturn, Uranus and possibly Venus and Neptune. Optical lightning has been detected at Jupiter, as well as whistlers. As with classical optical spectroscopy, the detection of radio waves over a broad range of frequencies is a powerful remote sensing diagnostic of processes acting on planets, yielding information about sources and/or the intervening medium between source and detector.

[3]   A particularly intriguing case concerns the detection by Voyager-1 and -2 of bursts of broadband emission called Saturn Electrostatic Discharges (SEDs) during their fly-bys of the planet in 1980 and 1981. These discoveries prompted a robust series of discussions and controversies about source mechanisms, i.e., whether SEDs were due to lightning deep in the atmosphere or to discharges above the atmosphere in the rings. Excellent summaries of proposed mechanisms and challenges to them appear in *Burns et al.* [1983] and *Kaiser et al.* [1984a]. With lightning as the currently accepted source, there are significant implications for Saturn's ionosphere since it must allow the waves to escape into space. This is the scenario to be investigated here, with a new ionospheric model prepared for the Cassini era of upper atmospheric research at Saturn.

[4]   The Voyager SED measurements involved fundamental assumptions about atmospheric science at Saturn. First, its troposphere must have been convectively active on a relatively continuous basis. Each of the flyby observing periods spanned several UT-days, and there is no reason to suspect that lightning occurred only during those periods in 1980 and 1981, or that the frequency spectra of the radio bursts changed from day to night. Similarly, the ionospheric structure during those periods had to be typical for that epoch, and thus no special ionospheric conditions were present temporarily due to some unusual activity (e.g., an eclipse). Given those assumptions, then perhaps the two most important characteristics of the SED detections were their occurrence rates and frequency spectrum: (1) the sources were from "active regions" that rotated approximately with the planet, and thus they were available at all local times; (2) the detected SED frequency spectra varied in local time (LT), not because the source was LT-dependent, but because the satellites sampled various LTs as they sped past the planet. The interesting finding was that daytime SEDs had $f_{min} \sim 3$ MHz, while nighttime detections had $f_{min} \sim 0.3$ MHz. This SED diurnal pattern was attributed to the changes in the medium between source and detector, specifically, to Saturn's ionosphere.

[5]   Saturn's lightning thus acted as a type of natural ionosonde, with a bottom-side transmitter and a topside detector. The lowest observed penetration frequencies (f_{min}) were assumed equal to the ionospheric plasma frequencies (f_p), which could be used to estimate the peak electron densities (N_{max}) during a Saturn day. The conclusion was that N_{max} varied diurnally from $\sim 10^3$ e/cm^3 ($f_p = 0.3$ MHz) at night to a value of $\sim 10^5$ e/cm^3 at midday ($f_p = 3-5$ MHz). While the latter (high N_{max}) did not present difficulties to the earliest models of Saturn's ionosphere, the former (low N_{max}) did, and so *Burns et al.* [1983] suggested that shadows cast by Saturn's rings might cause holes in its

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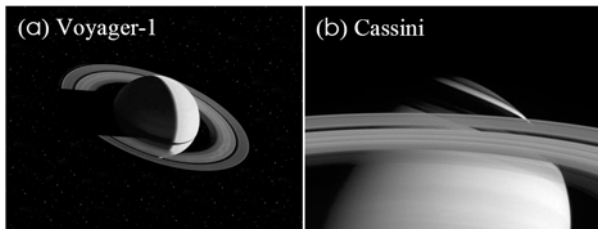[4]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

Figure 1. (a) Image taken on 1 November 1980 by Voyager-1 showing a strong narrow shadow cast on the equatorial region of the planet's atmosphere by the rings. (b) Image acquired by the Cassini spacecraft on 10 May 2004, showing a complex set of ring shadows cast over a large portion of northern hemisphere.

ionosphere through which the lowest frequency SED waves could pass.

2. Early Models of Saturn's Ionosphere

[6] Prior to the acceptance of SED-relevance to Saturn's ionospheric diurnal morphology, the few radio occultation measurements had already challenged a theory that predicted peak electron densities of $\sim 10^5$ e/cm^3 at Saturn [*McElroy*, 1973]. The measurements near dawn and dusk gave values closer to 10^4 e/cm^3, and thus additional loss processes were needed. Two mechanisms were proposed to enhance the ion loss chemistry, one involving an influx of water from the rings, converting H^+ to H_2O^+ [*Connerney and Waite*, 1984; *Connerney*, 1986], and a second to convert H^+ ions to H_3^+ via reactions with vibrationally-excited H_2 (suggested as a possibly important mechanism by *McElroy* [1973], explored for Jupiter by *McConnell et al.* [1982], and discussed for Saturn by *Majeed et al.* [1991] and *Majeed and McConnell* [1996]). The crux of the problem was that if the dominant ionospheric ion were H^+, it would recombine very slowly with electrons, and thus the densities would be high and vary little from day to night. If the dominant ion were molecular, however, then dissociative recombination would be rapid and peak densities with lower magnitudes and LT-dependent patterns could emerge. With the SED-from-lightning interpretation gaining acceptance as an ionospheric diagnostic of a strong diurnal variation [*Kaiser et al.*, 1984b], both mechanisms were used in attempts to produce a 100-fold variation in peak electron density. *Moore et al.* [2004] have recently summarized past and current approaches to these issues using 12 separate simulations to explore parameter space possibilities. While additional chemical mechanisms can be invoked to match either the low nighttime values (10^3 e/cm^3) or the high daytime values (10^5 e/cm^3), no self-consistent solution could be found to match both extremes in the short (10-hour) Saturn day.

3. Cassini at Saturn

[7] While en route to Saturn, Cassini's radio and plasma wave instrument first observed an SED event in July 2003, but subsequent detections have been infrequent, giving the early impression that SED events are more episodic and less regular during the Cassini era [*Gurnett et al.*, 2005; *Kaiser et al.*, 2004; *Kurth et al.*, 2004]. One of the possible explanations offered is that lightning conditions have

changed on Saturn, i.e., the sources in 2004 are simply not as strong or frequent as found in the early 1980s. The mechanism proposed by *Kaiser et al.* [2004] is that the shadows cast by Saturn's great system of rings are very different in 2004 than the shadows in 1980–81, and thus the convective activity that drives lightning has changed substantially. As shown in Figure 1a, during the Voyager era the rings were very nearly in the plane containing Saturn and the Sun, and thus a relatively narrow shadow was cast upon the low latitudes of the planet, creating a type of long-lived eclipse that might lead to "hot" and "cold" areas narrowly separated, presumably fostering the development of turbulence. In 2004, the situation has changed with the rings tilted well above the Sun-Saturn plane (Figure 1b), casting broad shadows upon northern latitudes, resulting in presumably far milder gradients in tropospheric parameters, and hence little storm-induced lightning.

[8] In this brief letter, we explore the companion effects that ring shadowing would have upon the ionosphere, and thus examine if the medium that filters out which radio wave frequencies pass through the ionosphere also controls, and/or contributes to, the lower detection rate of SED by the Cassini instrumentation.

4. Model Studies

[9] The new Saturn Thermosphere-Ionosphere Model (STIM) involves a classic general circulation model for Saturn's thermosphere (I. C. F. Mueller-Wodarg et al., A global circulation model of Saturn's thermosphere, submitted to *Icarus*, 2005) that is subsequently coupled to ionospheric continuity equation calculations (photoionization, chemical loss and plasma diffusion) to yield global electron density profiles versus local time [*Moore et al.*, 2004]. As with previously published models, STIM's parameters can be tuned to yield N_{max} values that agree with radio occultation data, but the height of the peak density (h_{max}) remains underestimated. Given the dominant role of photochemistry in determining N_{max}, modeling SED scenarios as a differential simulation experiment can be done independently of h_{max} issues. STIM's incorporation of ring shadowing effects makes it a particularly useful tool for assessment of the *Burns et al.* [1983] mechanism of SED wave penetration through ionospheric holes.

[10] The Voyager and Cassini measurements pertain to different solar conditions. For Voyager-1 and -2, the solar fluxes (F10.7) at the times of their fly-bys were 209 and 230 units, respectively. For Cassini, from the onset of SED observations in July 2003 to the time of orbit insertion in July 2004, F10.7 ranged from 183 to 117 units. As described in detail by *Moore et al.* [2004], the role of ring shadowing is to provide an above-the-atmosphere opacity function that affects the latitude and local time patterns of photo-ionization far more dramatically than seasonal and solar cycle effects. Accordingly, we employ a fixed solar flux condition (F10.7 = 180) so that ring shadowing produces the only changes to be shown.

[11] Figure 2 shows the results of the STIM calculations for the Voyager-2 (Figures 2a, 2b, and 2c) and Cassini (Figures 2d, 2e, and 2f) conditions. In Figure 2a and Figure 2d, the geometry of ring shadowing effects is shown in opacity units for normal incidence. The opacity used in the calculations is the normal opacity divided by the sine of
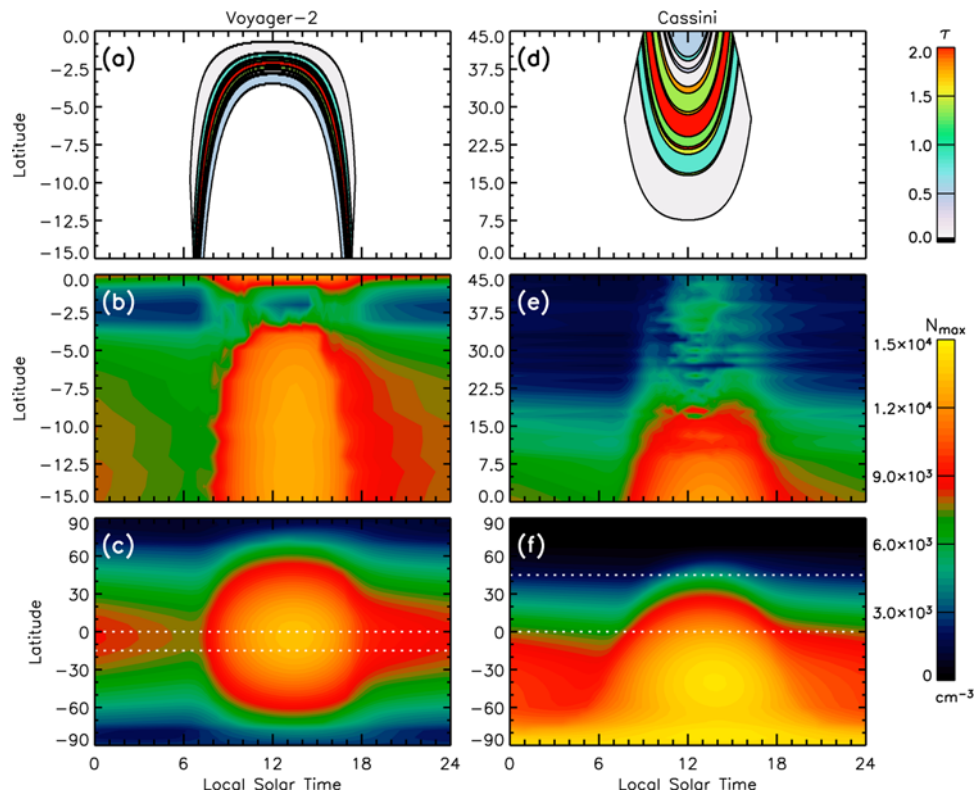
Figure 2. Results from the Saturn Thermosphere Ionosphere Model (STIM) for the Voyager flybys in 1980 and 1981 (equinox conditions), and Cassini's approach to the planet in 2004 (southern hemisphere solstice). For Voyager, (a) gives ring shadow geometry portrayed in opacity units for normal incidence, (b) the effects of ring shadowing upon ionospheric peak electron densities (N_{max}) over the $0–15°N$ latitude range, and (c) the global N_{max} versus local time patterns without ring shadowing. The right hand panels follow the same format for the Cassini conditions. The dotted lines in Figures 2c and 2f show the latitude regions covered in the upper panels.

the solar declination. Note that the equinox conditions for Voyager-2 involve a latitude range one-third that shown for Cassini's conditions. In Figures 2b and 2e, maps of N_{max} versus local time are given over the same latitude ranges depicted in Figures 2a and 2d. For comparison, Figures 2c and 2f give global simulation results when ring shadowing is ignored.

[12] Clearly, strong ionospheric depletions, with significant structure in space and time, result from ring shadowing. These may provide the ionospheric holes envisioned by *Burns et al.* [1983] that allow the lowest frequency SED signals to reach satellite receivers above the ionosphere. To show this in more detail, Figure 3a gives the minimum N_{max} values found throughout the day spanning latitudes ±60° latitude. During the Voyager era, the ionospheric depletions were highly confined to low latitudes. For Cassini, the rings shadow a far broader portion of the northern hemisphere, and cause (together with seasonal trends shown in Figure 2f) equally deep ionospheric depressions poleward of 20°N.

[13] In Figure 3b, the local times of the electron density minima are given using solid and dotted curves to facilitate comparisons with the N_{max} patterns in Figure 3a. The lowest N_{max} values occur just before sunrise (i.e., 06 LT at all latitudes for Voyager's equinox case, and from ~03 to 09 LT for the Cassini's solstice case). For the Voyager case, the near-equatorial ionospheric hole also extends into the daytime period (see Figure 2b). Since only high

frequency SEDs were seen during the daytime hours, we propose that the trough structure was just too narrow for radio penetration at low frequencies, or that daytime lightning did not occur precisely below the trough, or it
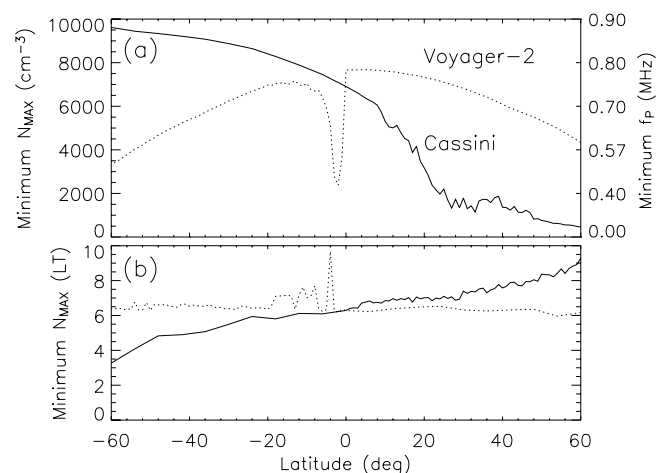

Figure 3. (a) The lowest diurnal value of peak electron density (N_{max}) versus latitude from the model results in Figure 2. Corresponding plasma frequencies are shown on the right hand axis. (b) Local times of the minimum N_{max} values shown in Figure 3a.
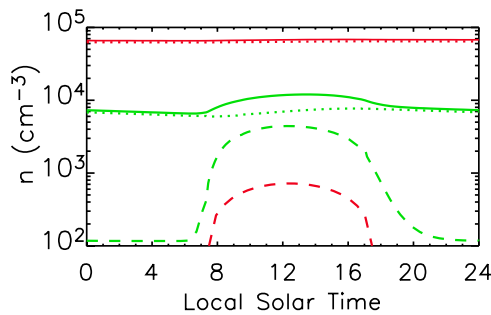
Figure 4. Two diurnal patterns for peak electron density for equinox conditions at a latitude (30°N) not affected by ring shadowing during the Voyager epoch. The red curves give N_{max} (solid line), the H^+ density (dotted line) and the H_3^+ density (dashed line) when the loss process due to vibrationally excited H_2 is removed from the chemistry. Note the absence of a diurnal variation and correspondingly high values of N_{max}. (Separate calculations using ring shadowing with this simulation also lead to confined regions of low peak density, but not of the severe form shown in Figure 2b). The green curves portray the same parameters as in Figure 2a, but with the H_2 vibrational reaction included at its nominal rate value, as in work by *Moore et al.* [2004]. Note that it results in lower N_{max} values that have a diurnal variation.

did not have low frequencies. Clearly, detailed ray-tracing simulations are needed to resolve such cases, and these are planned. Observations and modeling are also needed of the source mechanisms for lightning on gas giant planets [e.g., *Little et al.*, 1999; *Ingersoll et al.*, 2000].

[14] The overall message to come from Figure 3 is that electron density values nearly an order of magnitude lower than those for an unshadowed Saturn can account for the low frequency SED events detected by Voyager at nighttime. This is consistent with the fact that the Voyager radio receiver had no stringent directional constraints to satisfy. Thus, the ionospheric depletions near the equator contributed the low frequency cut-off attributed to the nighttime ionosphere. For the Cassini case, there is clearly no problem finding regions of low electron density at all LTs in the northern hemisphere. A broad spectrum of SEDs should therefore be seen if lightning occurs in the northern hemisphere. Yet, early in its mission, Cassini has been near $16-17°S$ where the ionosphere is robust. If SED signatures are not routinely observed [*Gurnett et al.*, 2005], then one might well conclude that sources of lightning are not prominent at high latitudes [*Kaiser et al.*, 2004]. If SEDs came directly from sub-satellite latitudes, Figure 2 shows that the summer solstice ionosphere would only allow penetration at $f > 1$ MHz.

[15] The second half of the SED dilemma deals with the high end of the SED spectrum, i.e., that daytime detections at $3-5$ MHz correspond to $\sim1-3 \times 10^5$ e/cm^3. This remains a difficult problem for modelers. *Moore et al.* [2004] showed results for twelve possible diurnal variations of N_{max} at a latitude unaffected by ring shadowing.

As described in their Table II, the elimination of the key reaction between H^+ and vibrationally excited H_2 has the largest impact on the overall loss process, moving daytime values of N_{max} at noon in the nominal model from 1.9×10^4 to 1.6×10^5 e/cm^3. The long-standing problem with that adjustment is that the ionosphere is dominated by atomic ions that hardly suffer any recombination during the brief Saturn night, effectively eliminating a diurnal variation all together.

[16] The STIM simulations in Figures 2 and 3 used the latest SOLAR2000 irradiance model (v.2.25), one that yields even lower daytime electron densities than described by *Moore et al.* [2004]. In Figure 4, two diurnal patterns are shown to demonstrate the effects of enhanced loss by the H_2-vibrationally-excited reaction. The curves in green give the diurnal patterns for H^+ and H_3^+ (and their sum to give total electron density) at the ionospheric peak with this process included. For the red curves (without enhanced loss), the H_3^+ abundances are an order of magnitude less, and thus the diurnal pattern is dominated by the essentially constant H^+ values throughout the day. The conclusion to be drawn is that strong avenues of enhanced chemical loss may not be needed to satisfy a pronounced SED variation versus local time. With ring shadowing taken into account, portions of the planet can have N_{max} values considerably lower than typical daytime values by means other than strong recombination chemistry over vast regions of the planet. Enhanced loss rates from an influx of H_2O or from the H_2 vibrational loss process might then be reduced from their most robust formulations, thereby leading to a resolution of the long-standing inconsistency between SED observations and modeling of Saturn's ionosphere.

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